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ALTERNATIVE APPROACHES TO WATER RESOURCE SYSTEM SIMULATION.(U)
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ALTERNATIVE APPROACHES TO WATER RESOURCE SYSTEM SIMULATION

by

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Two techniques for simulating the operation of a complex water resource system are demonstrated. One technique uses a network analysis approach and the other uses a sequential search procedure as a solution technique. The two are applied to a simplified version of the proposed Texas Water System, including a major import facility and two major canal systems containing nine reservoirs or groups of reservoirs and three other major delivery points. The relative capabilities and effectiveness of the two (cont)

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20. ABSTRACT (Continued)

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INTERNATIONAL SYMPOSIUM ON MATHEMATICAL MODELLING TECHNIQUES IN WATER RESOURCES SYSTEMS

ALTERNATIVE APPROACHES TO WATER RESOURCE SYSTEM SIMULATION

By Leo R. Beard[1], Arden O. Weiss[2] and T. Al Austin[3], U.S.A.

ABSTRACT

Two techniques for simulating the operation of a complex water resource system are demonstrated. One technique uses a network analysis approach and the other uses a sequential search procedure as a solution technique. The two are applied to a simplified version of the proposed Texas Water System, including a major import facility and two major canal systems containing nine reservoirs or groups of reservoirs and three other major delivery points. The relative capabilities and effectiveness of the two simulation models are discussed and demonstrated in relation to detailed simulation of the operation under stochastic variations of inputs and demands in a 17-year period.

INTRODUCTION

The management of water resources is a primary component of managing total resources, and the development and operation of storage and transfer facilities will continue to be the most essential component of water management. However, increasing development of water resources and recognition of the fact that many noneconomic aspects of development must be considered have greatly increased the complexity of the planning process. Not only must a much larger number of alternatives be considered, but each alternative represents a complex problem of interrelated effects and must be evaluated with respect to many effects at many locations. At the present state of the art, it is not feasible to derive directly an optimum solution to most water resources planning problems, but it is feasible (although extremely difficult in the more complex applications) to simulate the proposed operation and to reasonably evaluate the effects of each alternative when operated according to specified rules under specified inputs.

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Planning of water resources development usually involves projections of increasing needs over long periods of time, and it is usually necessary to assure that early developments are consistent with long-range needs and potentials. Adequate simulation of long-range plans therefore involves the projections of resource availability and of needs over long periods and simulation of operations of dynamic development rather than or in addition to static levels of development. The simulation of dynamic development is similar to that for a static level, but it is far more important that dynamic development be simulated for many possible hydrologic sequences rather than for a single hydrologic sequence, such as repetition of recorded events. This is because the time of implementing each development step can be greatly influenced by the times of droughts or surpluses in a single sequence.

This paper concerns only the simulation process. It describes two approaches to simulation and illustrates these in application to a moderately complex system operating at a static level of development. One approach, developed by the Texas Water Development Board, uses a closed network for computing the transfer of water within the system during each computation interval, using a pricing or priority structure to control transfer and storage operations. The other approach, developed by The Hydrologic Engineering Center, uses a search sequence, supplying needs on a priority basis starting at the headwaters and working downstream during each computation interval, and attempting to maintain a specified distribution of storage at the end of each interval. Although the problem illustrated herein is confined to a fixed system and fixed level of demand, both models are capable of simulating the expansion of the system through project staging and of accepting changing levels of demand and supply.

EXAMPLE USED FOR COMPARISON

A highly simplified version of the proposed Texas Water System was used as a basis for comparing the two simulation techniques. In particular, many of the closed loops, where water could be pumped west at times and released eastward by different paths at other times, have been eliminated because of the inability of the HEC-3 model to simulate certain types of closed loops that do not ordinarily exist in water resource systems. A schematic diagram of the simplified system is shown in Figure 1 and pertinent reservoir data are given in Table 1. Several of the reservoirs in this system are each actually aggregates of smaller reservoirs.

Inflows, rainfall and evaporation quantities used are those recorded during the historical period of 1941 through 1957. Irrigation, municipal and industrial water requirements used are those for the level of needs projected for the year 2020, but corresponding to weather conditions for the historical period of 1941 through 1957. Monthly values of all quantities were used in both models, and all of these vary from year to year as well as from month to month.

Table 1 - Reservoir Storage Data

Reservoir	Capacity (ac-ft)	Min. Pool (ac-ft)
1	4,590,000	480,000
2	1,880,000	80,000
3	4,800,000	0
4	800,000	10,000
5	10,230,000	2,120,000
9	3,500,000	20,000
10	280,000	60,000
11	440,000	30,000
12	200,000	0

Active storage capacity in this system is 24 million acre-feet, which is about 1.7 times the average annual demand projected for the year 2020. Maximum use is to be made of intra-state supplies, and import of water is to be made only as necessary to assure a firm supply as needed during potential drought periods. Timing of the importation of water is dependent on the highly erratic nature of available water surplus to out-of-state needs, which occurs only in 4 or 5 months of most years. In some dry years, no water is available for import.

System characteristics, input and demand quantities are identical for application of both simulation models. The methods of storing available water, importing water, computing evaporation and providing water to the service points are somewhat different. In the application of each model, an attempt was made to satisfy demands at all points with minimum import to the extent possible, but, if severe shortages are unavoidable, to cause those shortages to occur at location 3 (West Texas).

The indicator used to express shortage severity is that originally proposed in 1963* and is the sum of the squares of annual shortages for 100 years of operation, if each annual shortage is expressed as a ratio to the annual demand. This indicator (called the shortage index) is useful, particularly for planning studies, because the impact of shortages is approximately proportional to the square of the amount of annual shortage, provided that every effort is made to minimize the impact in actual operation through short-term forecasts and judicious declaration of shortages for the less vital services.

*Beard, L. R., Estimating Long-Term Storage Requirements and Firm Yield of Rivers, IUGG Berkeley General Assembly, 1963.

THE SIMYLD MODEL

SIMYLD is a general purpose simulation and optimization model used to analyze the hydrologic responses of a multireservoir water resource system. The model optimizes the movement of water on a monthly basis while striving to meet a set of prespecified demands in a given order of priority. The model is structured to accept any type of water resources system configuration.

SIMYLD utilizes a procedure for optimizing the cost of fluid transfer within a capacitated network. A solution is produced for a finite time step (one month) and the analysis moves forward in time in a stepwise fashion. The out-of-kilter linear programming algorithm for the analysis of capacitated networks is the basic mathematical tool used. The objective function to be optimized is the sum of the "false cost" which are represented by the priorities assigned to each node. In addition to the priorities for meeting demands, a set of priority numbers for maintenance of a given storage level at each storage facility is included in the objective function. In addition, SIMYLD is capable of determining the firm yield of a multiriver basin system, that is, the maximum demand that can be placed on any one reservoir within the system with no shortage and meeting prespecified demands at the other reservoirs in the system.

SIMYLD is not designed to minimize the total economic cost of the transfer of water; however, the SIM-IV modelling system, developed by the TWDB, utilizes the same basic computational algorithms to minimize the discounted capital and annual operational cost of water transfers. As presently structured, SIMYLD operates only the conservation storage of a set of reservoirs and therefore is not capable of simulating flood operations and hydroelectric power generation. Additional information on the SIMYLD and SIM-IV models can be obtained from the TWDB.

THE HEC-3 MODEL

The Hydrologic Engineering Center computer program, HEC-3, Reservoir System Analysis, performs a traditional simulation of the operation of a system of reservoirs having specified inflows, demands and operation criteria. Simulation of multipurpose operation usually employs a monthly computation interval, and this simulation must be supplemented by special short-interval studies, which can be accomplished by separate runs of the same computer program.

Operation is controlled by an equal number of independently specified storage levels at each reservoir. When water is stored within the upper one (or more, if specified) ranges, flood-control releases are made. When there is insufficient water to fill the bottom range, releases are reduced to priority requirements. Intermediate levels control the distribution of remaining water among all reservoirs, with the objective of maintaining all reservoirs at the same specified level. Thus, if a

particular level is specified low in one reservoir and high in another, the first reservoir would tend to be drawn down earlier than the second. During each computation interval, the total flows that would occur at each point if all upstream reservoirs draw down to each successive level, subject to previously imposed constraints, are established, and the tentative operation of each reservoir is then obtained by interpolation to the desired flow.

The computation for each interval consists of adding inflow and removing evaporation at each reservoir, supplying diversion and then supplying river flows to the extent that water is available. Diversion and flow requirements at any point in the system are supplied from any or all reservoirs upstream of that point, except for those specified as not serving that point, and releases from upstream reservoirs are selected so as to keep the remaining storage in the specified balance insofar as possible. Demands are thus supplied at each control point in turn, making sure that all upstream points are examined and served for each priority before any downstream location is. Operation of any reservoir is thus subject to change until all points have been examined, at which time end-of-period storages are established and the next computation interval is started.

At the end of each year, detailed operation data are printed as desired, so that any aspect of the operation can be critically examined. At the end of the operation study, a great variety of summaries can be provided, including detailed economic evaluations. Although some automatic iteration capability exists, improvement of the system design or operation criteria is effected by careful examination of system performance, determination of the controlling factors, manual modification, and repetition of the operation study.

The program is highly flexible in the degree of detail with which inflows, evaporation, demands and system characteristics can be specified. It can therefore be used efficiently for preliminary evaluations using approximate data or for final design analysis using extremely elaborate data. It is a water quantity model and simulates reservoir storage, evaporation, river flows, diversions and return flows.

SOLUTION BY SIMYLD

Simulation of the operation of the example system by use of SIMYLD required simply that each reservoir and service point be given a network node number and upper and lower storage limits, and that each canal be given a link number, the direction leading from one specified node to another specified node, and upper and lower conveyance capacities. The program then provided a balancing node from which inputs to the other nodes emanate and to which demands and spills flow. Connecting links for the balancing node are also automatically provided.

Inflows, evaporation and demands were supplied for each computation interval (month), and a linear programming solution determined flows in

all links, from which storages were calculated as a starting condition for the next computation interval. The objective function is the total cost of storage and flows at all nodes and links and is minimized subject to system constraints, supplies and demands. Cost functions can vary with reservoir storage at each node, thus lending great flexibility in formulating operation rules. These functions were manually adjusted as necessary to cause the system to import water and distribute available water in storage as necessary in order to provide needed services at minimum cost insofar as possible.

No modification of the model was necessary for application to the example problem. All demands were met except during the critical drought period from 1953 to 1957, when severe shortages occurred only at the West Texas terminal reservoir. Imported water was used only as necessary, and all in-state supplies were used during the critical drought period.

SOLUTION BY HEC-3

As pointed out previously, the HEC-3 model does not have provision for closed-loop operation such as would occur when water is diverted from a downstream point and fed back to an upstream point. Such an operation occurs in water development projects only when some types of pumped-storage facilities or some types of bifurcation facilities are provided. In such cases, specially tailored routines are necessary in order to utilize HEC-3.

The basic structure of HEC-3 is designed for application to an ordinary river tributary structure. In order to simulate the operation of the simplified Texas Water System configuration specified herein, the canal is considered as the main river system, except that reservoirs feeding into that system would spill any excess flows out of the system instead of into the canal.

The closed loop between reservoirs 4 (Marshall) and 5 (Rockland-Sam Rayburn-Toledo Bend combined) was simulated by a special provision to maintain the two reservoirs proportionately full, subject to transfer capacities of the connecting facility.

Storage balance levels were selected such that water would be transferred westward early enough during wet periods to assure that all reservoirs would be full at the start of a critical hydrologic sequence. These target levels were maintained constant throughout the calendar year, but they can easily be varied seasonally for the purpose of refining or improving the operation criteria. In order to keep the comparison simple, no flood-control space was specified in any of the reservoirs. Likewise, no buffer space was provided for specifying priority flow releases when reserves are low. This feature of the model would be used in refinement studies in order to assure municipal and other priority services during extreme drought periods.

As in the case of SIMYLD, simulation of the project operation for the historic hydrology, with imports limited to 50,000 cfs when available,

showed extreme shortages during the critical drought period (June 1953 to January 1957) at the West Texas terminal. Some shortages occurred at practically all service locations, but these others are all minor and also were restricted to the one critical drought period. Otherwise, quantities were very similar to those shown in the SIMYLD study.

COMPARISON OF TECHNIQUES

Both techniques appear to simulate the operation of a complex water resource system as accurately as the pertinent functions and features of the system can be described. The principal differences are:

(a) SIMYLD uses a network simulation and solution technique, whereas HEC-3 uses a system search routine and cannot simulate the operation of some types of closed loops without special programming.

(b) SIMYLD uses a linear programming algorithm for computing the optimum operation of the entire system for each computation interval, whereas HEC-3 provides releases in accordance with fixed operation rules based on storage and use schedules. In the case of SIMYLD, incompatible requirements are possible, in which case no solution (infeasible solution) results and a constraint must be changed manually.

(c) Operations are controlled in SIMYLD by a system of delivery and storage priorities (reflecting relative values of water), in relation to specified storage balancing levels, whereas HEC-3 specifies the balance of storage desired among the various reservoirs for any amount of total system storage and provides this distribution of storage subject to water availability in excess of demands at the various locations.

Both models can simulate system performance with fidelity and reasonable computation effort. Neither can automatically derive an optimum plan of development or an optimum operation rule, although an iteration routine could be developed for this purpose. There is some indication that the computation speed of the SIMYLD model is about twice as fast as that of HEC-3. This is greatly affected by the amount of print-out obtained.

As an effective means of comparing system performance in the two simulation studies, the shortage index defined above was computed for each service point. A comparison of shortage indices obtained in the two simulations is given in Table 2. It may be noted that the shortage index for location 3 indicates that the plan tested would result in extremely severe shortages on occasions, and hence a better configuration or a smaller demand schedule should be considered. The plan selected for the purpose of this comparison is an arbitrary plan, and it is not the purpose of this study to produce a better plan, but simply to compare two methods of simulating the operation of any such plan of development.

Table 2 - Comparison of Shortage Indices

Location	SIMYLD	HEC-3
1	.00	.06
2	.00	.10
3	5.78	4.64
4	.00	.00
5	.00	.03
9	.00	.33
10	.00	.06
11	.00	.05
12	.01	.09
13	.00	.14
14	.00	.14
15	.00	.24
16	.00	.00
17	.00	.24

CONCLUSIONS

The complexity of water resource problems requires that design and operation plans be examined in the degree of detail that is only possible with extremely elaborate system simulation models. Both such models demonstrated herein produce satisfactory and effectively equivalent results for a problem of the scope illustrated herein. The SIMYLD model has the advantage that practically any system configuration can be simulated, whereas the HEC-3 model must be specially adapted if a system permitting closed-loop transfers of water is being simulated. The HEC-3 model has been successfully applied to a great variety of water resource systems, including those operating for flood control, system power generation, variable-priority water supplies, trans-basin diversions, and return flows from upstream diversion, whereas the SIMYLD model is relatively new and has been applied only to variations of the problem described herein.

These modelling capabilities are not intended to be all-powerful methods that will provide a detailed quantitative solution to every problem; nor do the modelling capabilities represent an exact simulation of the prototype. They do, however, represent mathematical techniques that approximate the prototype at various degrees of fidelity and provide information at varying levels of accuracy, in a manner helpful to the evaluation of and the selection among viable alternatives.

It is within these limits of applicability that they are intended to function. That is, not to replace the experience and judgment of the planner or design engineer, but to be responsive to their needs by helping them to understand the processes and interactions at work in complex water resource systems.

The highly complex nature of the modern water resource development plans precludes a simple analysis and evaluation of the alternative ways to implement a plan. This analysis and evaluation must consider the total feasibility of each alternative from economic, technical, ecological, and social viewpoints and must be performed within a reasonable framework of time and money. The modelling techniques discussed herein are capable of providing this to the water resource planner and thereby capable of helping find "most reasonable" solutions to the water resource problems which are so important to all.

ACKNOWLEDGMENT

The SIMYLD model was developed by the Texas Water Development Board and Water Resources Engineers, Inc., of Walnut Creek, California, with support from the Office of Water Resources Research. The HEC-3 model was developed by The Hydrologic Engineering Center of the Corps of Engineers. While much of the model development work was done by others, views and conclusions expressed herein are those of the authors and do not necessarily reflect those of the Texas Water Development Board, of the Corps of Engineers or of the Water Resources Council.

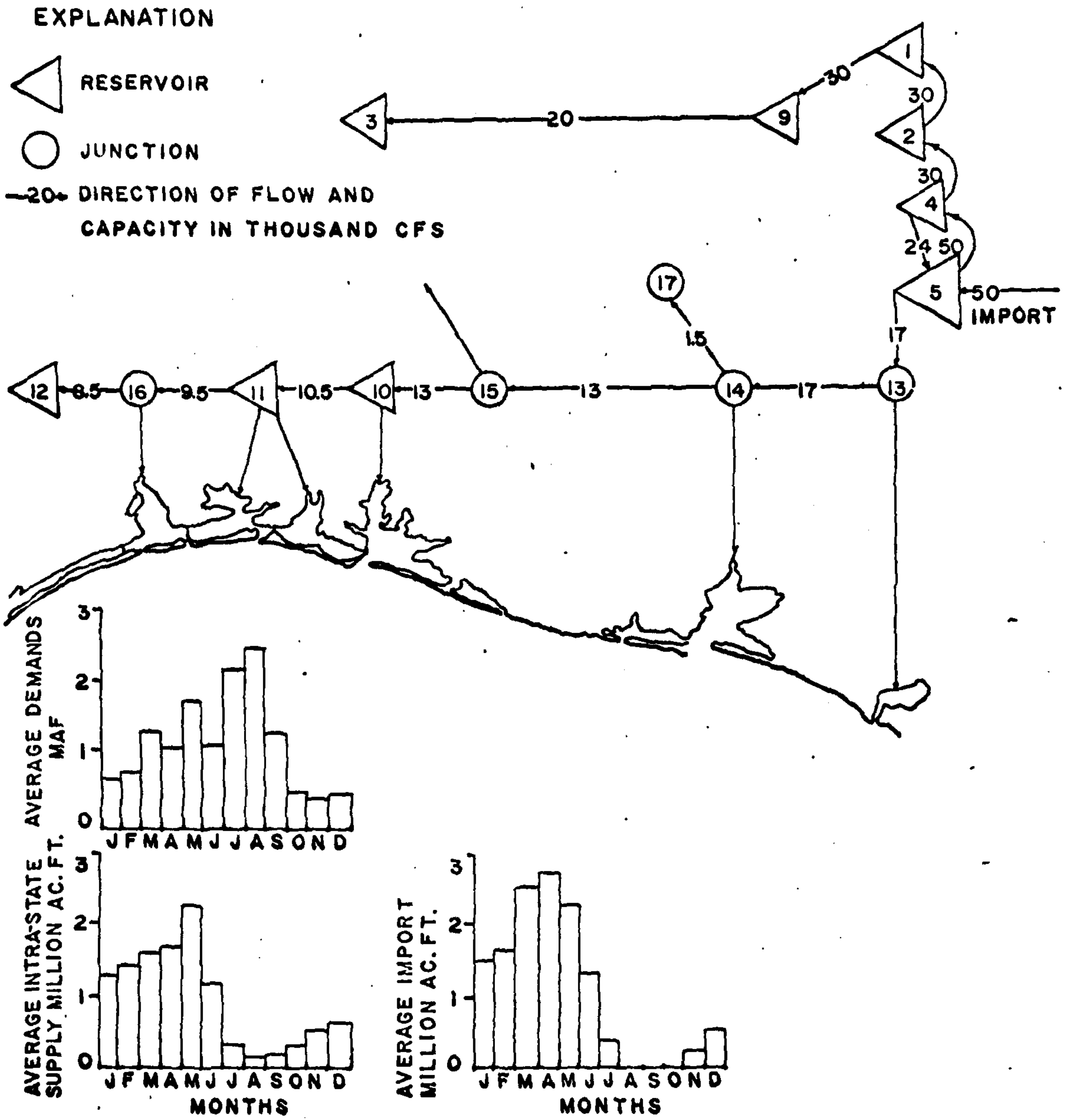

FIGURE 1

SCHEMATIC DIAGRAM OF THE EXAMPLE WATER SYSTEM

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